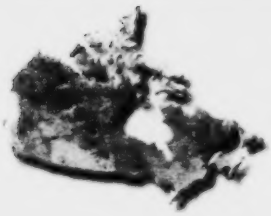

Incorporating Present and Future Climatic Suitability into Decision Support Tools to Predict Geographic Spread of the Mountain Pine Beetle

T. L. Shore[1], W.G. Riel[1] and A. Fall[2]

Mountain Pine Beetle Working Paper 2008-10

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Abstract

The main goal of this project was to adapt existing mountain pine beetle (MPB) decision-support tools to incorporate climatic suitability information to refine the spatial characterization of present climate and to support assessments of future climate. These tools include susceptibility and risk rating systems, the MPBSim stand-scale MPB population model, the landscape-scale SELES-MPB population model, and graph-based connectivity methods. We made significant advances on all of these, resulting in a suite of tools with increased capabilities and generality. During the course of this project, we also provided decisions support in the specific areas of study, in particular Dawson Creek and central-western Alberta.

The basis of the climatic suitability was the work of A. Carroll et al. (2004) which produced estimates of MPB climatic suitability in five classes across western Canada, for historical, existing and future climates. Future climate information was derived from global circulation models such as the CGCM model. They input general climate information into the BioSim tool, in conjunction with topography and other variables relevant to downscaling for MPB, to produce the MPB climatic suitability maps. We used these maps to create an adaptation of the MPB susceptibility and risk rating system that replaced the coarser location factor (based on latitude, longitude and elevation) with MPB climatic suitability. It is important to note that the MPB climatic suitability refers only to climatic conditions relevant for MPB survival and reproduction, while the susceptibility rating system incorporates pine host information.

We also modified MPBSim, a stand-scale population model, to utilize the MPB climatic suitability information. In previous applications, MPBSim was adapted to local conditions via a calibration process using local weather information. In some senses, this calibration process resulted in a reasonably precise adjustment to local conditions. However, it was also fairly labour intensive and didn't account as well for spatial variability. Our approach here was to use climatic suitability to both increase spatial precision as well as produce outputs that can be readily adapted to different stand and landscapes.

The SELES-MPB landscape-scale population model scales MPBSim dynamics to broad spatial areas. We modified this tool to utilize the revised MPBSim output. This supports more rapid adaptation to other landscapes, as well as allows examination of potential effects of future climate. Our Dawson Creek analysis indicated that beetle management in the Dawson Creek area could significantly affect the spread and impact of the beetle outbreak over the next 10 years, provided that high levels of fell and burn and survey efforts are maintained. Estimated impacts are significantly affected by external pressure from the main outbreak, as estimated using the provincial-scale BCMPB projection. If mountain pine beetle populations can be held low until the main outbreak subsides (which will likely occur within the next five years due to availability of hosts), management should be able to curtail major losses in the Dawson Creek area.

In areas with new or no current MPB attack, especially in areas within the expanding range, there is relatively high uncertainty of how the MPB may spread, such as in central-western Alberta. We developed graph-based connectivity methods to assess the spatial pattern of high susceptibility hosts across broad regions, under historic, existing or future climates. This information has been useful to help prioritize and rank stands for treatment in areas of imminent or future risk, and to identify areas for which treatment has no benefit.

Résumé

L'objectif principal du projet était d'adapter les outils d'aide à la décision existants, relatifs au DPP, et d'y intégrer l'information sur les conditions climatiques favorables, afin d'améliorer la caractérisation spatiale du climat actuel et d'appuyer les évaluations du climat futur. Ces outils comprennent des systèmes de cotation de la vulnérabilité et des risques, le modèle de population du DPP à l'échelle du peuplement MPBSim, le modèle de population à l'échelle du territoire SELES-MPB et les méthodes de connectivité fondées sur les graphiques. Nous avons fait des progrès importants à l'égard de tous ces modèles et avons créé une gamme d'outils plus performants et de portée générale. Tout au long du projet, nous avons également aidé des régions particulières à prendre des décisions, surtout Dawson Creek et la région Centre-Ouest de l'Alberta.

Le travail de A. Carroll et coll. (2004) a servi de fondement aux conditions climatiques favorables. Leur travail a fourni des estimations sur les conditions climatiques favorables au DPP, dans 5 catégories dans l'Ouest du Canada, pour les climats passés, présents et futurs. L'information relative au climat futur est tirée de modèles de circulation mondiaux, comme le modèle de circulation générale (MCG) du Canada. Ils ont utilisé des renseignements climatiques généraux pour alimenter l'outil BioSim, conjointement avec la topographie et d'autres variables pertinentes pour l'étude des phénomènes de sous-échelle, en lien avec le DPP, afin de produire les cartes sur les conditions climatiques favorables au DPP. Nous avons utilisé ces cartes pour créer une adaptation du système de cotation de la vulnérabilité et des risques pour le DPP, lequel a remplacé le facteur de localisation grossier (en fonction de la latitude, de la longitude et de l'altitude) par les conditions climatiques favorables au DPP. Il est important de noter que les conditions climatiques favorables au DPP renvoient uniquement aux conditions climatiques favorables à la survie et à la reproduction du DPP, tandis que le système de cotation de la vulnérabilité tient compte de l'information sur l'hôte.

Nous avons également modifié le modèle MPBSim, un modèle de population à l'échelle du peuplement, afin d'utiliser l'information sur les conditions climatiques favorables au DPP. Dans les applications antérieures, le modèle MPBSim était adapté aux conditions locales au moyen d'un processus de calibrage fondé sur les renseignements météorologiques locaux. Dans une certaine mesure, ce processus de calibrage se traduit par un ajustement raisonnablement précis aux conditions locales. Toutefois, le processus a mis à contribution beaucoup de main-d'œuvre et a quelque peu fait abstraction de la variabilité spatiale. Notre approche consistait à utiliser la vulnérabilité climatique pour renforcer la précision spatiale et produire des données adaptables aux différents peuplements et territoires.

Le modèle de population SELES-MPB à l'échelle du territoire pondère les variations en fonction des zones géographiques. Nous avons modifié cet outil pour utiliser les données MPBSim révisées. Ce modèle s'adapte plus rapidement aux autres territoires et permet d'examiner les répercussions possibles du climat futur. Selon l'analyse que nous avons réalisée à Dawson Creek, la gestion des dendroctones pourrait avoir une incidence considérable sur la propagation et les répercussions du pullulement du dendroctone au cours des 10 prochaines années, à condition de maintenir les niveaux élevés d'abattage, de brûlis et d'enquête statistique, conformément à un document de travail du Programme sur le dendroctone du pin ponderosa. Les pressions externes, relatives à la pullulation principale, ont des répercussions considérables sur l'incidence présumée, conformément aux estimations faites au moyen de la projection du BC Provincial Scale Mountain Pine Beetle Model (BCMPB) à l'échelle provinciale. Si l'on parvient à maintenir les populations de dendroctone à un niveau faible jusqu'à ce que la pullulation principale diminue (ce qui devrait

se produire dans les cinq prochaines années en raison de la disponibilité des hôtes), il devrait être possible de limiter les pertes dans la région de Dawson Creek.

Dans les régions où le DPP n'est pas revenu ou n'est pas présent actuellement, surtout dans les régions élargies, comme le Centre-Ouest de l'Alberta, nous ne savons pas comment le DPP pourrait se répandre. Nous avons élaboré des méthodes de connectivité fondées sur les graphiques pour évaluer la répartition spatiale des hôtes très vulnérables dans les régions élargies, compte tenu du climat passé, actuel et futur. Ces données nous ont été utiles pour classer par ordre de priorité les peuplements à traiter dans les régions à risque, dans l'immédiat ou à l'avenir, et déterminer les régions dans lesquelles le traitement ne serait d'aucun avantage.

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1 Introduction

The mountain pine beetle (*Dendroctonus ponderosae;* MPB) is causing devastating losses to the forest resources of British Columbia and is spreading into Alberta. Management strategies directed at minimizing losses to mature pine stands include reducing beetle populations by direct control methods (harvesting, single tree treatments) or preventative management. Direct control actions are usually reactive management decisions made during beetle epidemics whereas preventative management actions are proactive decisions made to reduce landscape level susceptibility to the mountain pine beetle.

Due to scarce resources, tools are required to assist managers in prioritizing areas for treatment and for assessing landscape scale risk of attack. The Canadian Forest Service has developed a number of stand-level tools for this purpose. The Stand Susceptibility and Risk Rating System (Shore and Safranyik 1992, Shore et al. 2000) is used widely to identify the relative potential for, and likelihood of, loss of stand basal area to the mountain pine beetle. Two stand level population dynamics models have been developed: a very detailed, process-based model (Safranyik et al. 1999), and a less detailed, but more management-oriented model called MPBSim (Riel et al. 2004). MPBSim models the numbers of beetles attacking and emerging from trees each year of the infestation as well as tracks the numbers, diameters and volumes of live and dead trees. Many management decisions, however, are based on the landscape level and require spatial information.

To provide a management decision support tool that would extend MPBSim to the landscape level we required a spatial modelling environment in which we could disperse beetles to surrounding areas using actual forest inventory and geospatial data. The Spatially Explicit Landscape Event Simulator (SELES) (Fall and Fall 2001) was selected as an ideal modelling environment for this purpose. MPBSim has been linked with SELES, incorporating a dispersal model and management models (harvesting and single tree). The integrated models are called SELES-MPB.

The SELES-MPB provides a decision support tool that enables managers to address a number of questions regarding the mountain pine beetle. Through a probabilistic approach, likely scenarios of mountain pine beetle spread and impact can be studied. By comparing model runs under several management scenarios, the effectiveness of different management decisions on reducing the spread and impact of the mountain pine beetle can be examined. Operational studies have been conducted using SELES-MPB including the Kamloops Forest District, Lakes Timber Supply Area, the Lignum IFPA, Morice Timber Supply Area and the Foothills Model Forest (Fall et al. 2001, 2002, 2003a, 2003b, 2004).

Carroll et al. (2004) have developed climatic suitability maps for the mountain pine beetle based on a model developed by Safranyik (1999). Using BioSIM (Régnière et al. 1995), a software tool for use in forecasting events in the seasonal biology of insect pests, surfaces can be produced for the landscape identifying areas of climatic suitability for the beetle. Using climate change models, surfaces of climatic suitability for the mountain pine beetle under future climate change scenarios can be developed. Early work has suggested that the suitable range for the mountain pine beetle is expanding in British Columbia and Alberta. There is concern that the range could expand to include the jack pine forests, which extend across Canada. By integrating the work on climatic suitability into the existing mountain pine beetle models we can increase the sensitivity of these models. This is because the existing climatic information in the models is based on general zones modified by elevation, latitude and longitude, or on historic average climate, whereas climatic

suitability is based on location-specific climatic factors specifically related to mountain pine beetle biology and based on weather station data.

1.1 Project Objectives

The objective of this project was to further develop and improve the Mountain Pine Beetle Decision Support Systems, including the Susceptibility and Risk Rating System, MPBSim and SELES-MPB by incorporating climatic suitability information into these systems. During the course of the project, we also identified the need for new landscape-scale risk assessment tools for examining patterns of hosts across broad regions with no historic MPB information. We adapted methods from graph-based connectivity analysis for this purpose. A further objective was to use these modified models to examine the potential for mountain pine beetle spread and impact under climate change scenarios in northeastern BC and central-western Alberta.

Climatic suitability surfaces have been produced at appropriate scales in ArcView for British Columbia and Alberta. Surfaces were produced both for current climate and future climate using BioSIM (Régnière et al. 1995), using output from the CGCM-1 global circulation model. The Susceptibility and Risk Rating Systems were modified by replacing the current Location Factor with a Climatic Suitability Factor by using latitude and longitude to reference the climatic suitability surface. Climatic suitability information was incorporated into MPBSim by modifying weather-related functions with more specific information gained from the climatic suitability surface. The climatic suitability surface was incorporated into SELES-MPB at the appropriate scale, primarily to affect production and over-winter mortality. The changes in all of these models were tested and documented. We additionally adapted and developed graph-based connectivity methods (Fall et al. 2007) to examine MPB spread potential over broad areas, in particular areas into which the MPB are expanding (e.g., the boreal forest of Alberta). This provided a new tool to examine likely pathways of spread in areas with little MPB history, and hence where uncertainty in modeling potential spread is high.

Using current beetle, forest inventory and geospatial data provided by our cooperators, we evaluated susceptibility, risk, and potential spread and impact of the mountain pine beetle in the Dawson Creek area of northeastern BC and into Alberta with the modified models. Using the generated climatic suitability surfaces for future climates, we used SELES-MPB to examine the potential spread and impact of the mountain pine beetle in Dawson Creek and into Alberta over the next 15-20 years. We used the connectivity methods to examine likely pathways of spread into Jack Pine (*Pinus banksiana)* stands that start in central Alberta. We transferred our updated susceptibility and risk rating system that included climatic suitability to Alberta Sustainable Resource Development, who used it to create suitability maps for the entire province.

2 Decision-Support Tool Development and Application

2.1 Integrating climatic suitability into a mountain pine beetle susceptibility and risk rating system

The Shore-Safranyik risk rating system (Shore and Safranyik 1992; Shore et al. 2000, 2006) is an established risk rating system used extensively throughout British Columbia. To further refine this system, climatic suitability has been incorporated into the stand susceptibility component.

This helps to generalize the system for use in other regions, improves the spatial resolution of the system and allows the system to project stand susceptibility and risk under different climate change scenarios.

To incorporate climatic suitability in the stand susceptibility index, a "climatic factor" (CF) has been created which is a drop in replacement for location factor in the Shore-Safranyik susceptibility rating system. The values for climatic factor are directly based on the climatic suitability index (CSI) described by Carroll et al. (2004). Using a detailed mountain pine beetle model (Safranyik et al. 1999) and holding stand/beetle inputs constant, simulation runs for each climatic suitability zone were made. Any changes in projected beetle population are then due entirely to climate. The magnitude of these changes was then scaled from 0.1 to 1 to determine the weight of the CF.

CSI	CF
1	0.1
2	0.2
3	0.5
4	0.8
5	1.0

Under the old susceptibility system, the formulation of stand susceptibility (SSI) was defined as (Shore and Safranyik 1992):

SSI = P x A x D x L

Where:

P = % of susceptible pine basal area
A = age factor
D = Density factor
L = Location factor

Incorporating climatic suitability, stand susceptibility is now defined as:

SSI = P x A x D x CF

Where:

P, A, D are as defined above
CF = Climatic factor.

2.1.1 Tool Application: Transfer to ASRD for application to entire province of Alberta

GIS personnel in Alberta Sustainable Resource Development have implemented the updated version of the susceptibility rating system in ArcGIS and applied it to the entire province of Alberta (B. Wilson, pers. comm.).

2.2 Integrating climatic suitability into MPBSim stand-scale population model

The MPBSim population model (Riel et al. 2004) has been used to project stand level dynamics in many landscape scale simulations (e.g., Fall et al. 2001; 2002; 2003a; 2003b, 2006b), but has required specific climatic calibration for each individual landscape. In order to generalize MPBSim for use in any landscape, climatic suitability has been incorporated into the model.

The process of incorporating climatic suitability involved detailed analysis of each of the five climatic suitability zones (Carroll et al. 2004), examining temperature patterns across the zones and deriving estimates of MPB productivity for each of these zones based on these temperature patterns. The Safranyik model (Safranyik et al. 1999) was used to produce these productivity estimates, which were then used to calibrate MPBSim.

In effect, climatic suitability zone becomes an input into MPBSim, and projected MPB impacts and population growth will vary considerably from zone to zone to reflect differences in climate. This allows MPBSim to be employed in any stand or landscape where climatic suitability is known. This also adds greater flexibility to MPBSim, allowing it to be used to project MPB impacts under climate change projections.

In general, MPBSim has been applied in spatial landscape scale simulations through a method known as loose coupling (Riel et al. 2004). This required that MPBSim be pre-run for a specific landscape, using the landscape's existing forest inventory and climatic conditions as inputs. A large table representing MPB population projections for various stand and beetle conditions are generated and used in the landscape simulation to determine trees killed, beetle population survival and level of MPB dispersal.

With the integration of climatic suitability into MPBSim, a general table representing MPB population projections for any climatic condition has been generated. No longer is there a need to tailor MPBSim projections for a specific landscape, provided climatic suitability is known.

2.2.1 Tool Application: MPBSim Simulations using Climatic Suitability

The general MPBSim table has been applied in a landscape scale simulation in the Dawson Creek timber supply area (Fall et al. 2006b), and was used for calibrating BCMPB (Eng et al. 2005).

2.3 Integrating climatic suitability into SELES-MPB landscape-scale population model

The core of the SELES-MPB landscape model was developed largely through prior projects with the B.C. Ministry of Forests and Range (Fall et al. 2001; 2002; 2003a; 2003b). The mountain pine beetle models were derived by the authors and Les Safranyik (emeritus, Pacific Forestry Centre, Canadian Forest Service). The general concept involves using geographic, forest inventory, weather and beetle-infestation data for the study area, and projecting it forward using a landscape model to evaluate the course of the infestation, primarily in terms of area infested and volume killed by the beetle. The beetle outbreak model is combined with management models for harvesting and fell and burn treatments, so that interactions between management and beetles can be assessed. The model is not designed to predict when an outbreak may end, but we usually artificially terminate it after 10 years, which is in line with expectations for collapse of most

outbreaks. Through comparison of various scenarios, potential benefits of beetle management can be identified. This information can then be used to assess impacts directly or to serve as input for further analysis of economic, social and ecological cost/benefits (e.g., by an economist or ecologist). Further details on this model and application can be found in Fall et al. (2004).

As part of this project, we incorporated climatic suitability information. This mostly involved adaptations to utilize the enhanced MPBSim outputs that included additional information on climatic suitability zone in conjunction with spatial information on climatic suitability. The advantages of this approach are:

- explicit inclusion of climatic suitability affecting MPB growth and mortality supports both increased spatial precision to capture variation in climate across a study area, and ability to introduce climate change information by statically or dynamically changing the spatial climatic suitability input map.
- increased generality of application because prior applications of SELES-MPB required calibration of MPBSim to the local climate conditions. Now, local climate conditions are captured in the spatial MPB climatic suitability layer used to index the enhanced MPBSim output table.

2.3.1 Tool Application: Dawson Creek Timber Supply Area Analysis

Mountain pine beetle attack in the Dawson Creek area in northeastern B.C. was first confirmed in February 2004. The main provincial outbreak had been expanding rapidly, and it appeared that the Rocky Mountains could provide the only opportunity for a break large enough to disrupt the beetle's spread. Spots detected in Dawson Creek most likely originated from the main outbreak and were transported over long distance via wind and through mountain passes. Growth rates, as indicated by green:red attack ratios, have been relatively low (compared to elsewhere in the beetle's range), but nonetheless showed potential for population growth. This suggested that weather has been sufficiently favourable to support an outbreak, whereas historic climate likely precluded outbreaks. Substantial effort in Dawson Creek has focused on dealing with detection and treatment of infestation spots, with cooperation among licensees, the forest service and parks. A landscape-scale projection of outbreak potential was deemed to be useful to inform this process and to help clarify some tradeoffs between options available. It could also help inform assessment of risk of spread into Alberta and the boreal forest.

The Dawson Creek Landscape Model (DCLM) was developed to assess the impacts of mountain pine beetle management activities in the Dawson Creek area (the Dawson Creek Timber Supply Area, Tree Farm License 48 and area parks) and to analyze the potential spread of the current beetle outbreak across this region and potentially into the boreal forest of Alberta. In addition to including MPB climatic suitability information, a key purpose of our analysis was to apply and refine a model methodology to evaluate the effectiveness of landscape-scale bark beetle-management activities in reducing losses to mountain pine beetle, and to analyze the potential spread of the beetle across the study area. Specifically, we aimed to address the question: what would be the likely trajectory and impacts from the current beetle outbreak under a range of alternative beetle-management regimes? To achieve this goal, we start with the current conditions and project likely outcomes under the various scenarios. The beetle outbreak terminates after 10 years, but the model may be run longer to assess the decay of killed merchantable wood over the following decade and the long-term implications on growing stock and other timber-supply indicators.

Using the best available inputs from inventory, weather data, management activities and infestation maps, the DCLM projects beetle spread on an annual basis. A range of scenarios was analyzed to assess expected impacts of management and assumptions regarding climate and external beetle pressure. The scenarios included:

(i) Starting conditions based on 2004 or 2005 survey information;
(ii) External mountain pine beetle pressure—assumed to be either no pressure (closed-world assumption), pressure based on 2004 levels, or dynamic pressure derived using the provincial-scale beetle model BCMPB (Eng et al. 2005);
(iii) Climatic suitability for mountain pine beetle based on either recent historical averages 1971 to 2000 or estimated near future climate 2001 to 2030 (Figure 1);
(iv) Management regime options that included general beetle management (i.e., similar to elsewhere in the province), current practices, salvage only, and no beetle management (no harvesting or single-tree treatments);
(v) Harvest levels that were either the current annual allowable cut (AAC) or a 50% increase;
(vi) Fell and burn levels based on levels applied in 2005, current targets, or other levels to assess the role of fell and burn in managing this outbreak.

Our focus was primarily on short-term effects (10 years of attack). The base case scenario was assumed to be current management practices under climate change conditions, with dynamic external pressure. As this analysis assessed over 60 scenarios, one of the challenges was to find clear methods to present results.

In addition to the integration and use of climatic suitability information, this analysis introduced several model additions to our landscape-scale population modeling methods:

- development of empirical methods to spatially approximate external dispersal pressure from main outbreak to the west of the Rocky Mountains;
- refinement of how beetle management unit strategies are dynamically identified, which allowed us to capture general beetle management policies as well as the specific current management zones applied in Dawson Creek

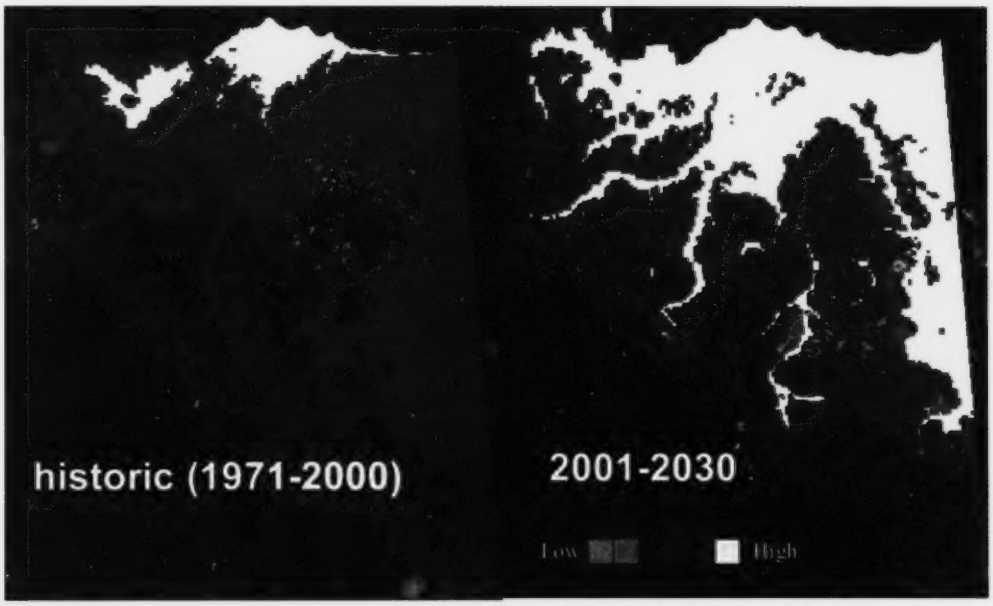

Figure 1. MPB climatic suitability information (A. Carroll, pers. comm.) from historic climate 1971-2000 and estimated future climate conditions 2001-2030.

Our analysis of the current beetle outbreak in Dawson Creek suggests that this outbreak is at an incipient scale, driven primarily by external pressure to the west and by changing climatic suitability (Figure 2), and that management efforts can have a significant impact in reducing losses (Figure 3). These results are consistent with conclusions from previous analyses in the Kamloops, Morice, Williams Lake and Lakes regions (Fall et al. 2001; 2002; 2003a; 2003b); i.e., applying fine-scale beetle management and accurate treatment of spot locations is important in areas with small- to medium-scale outbreaks, but has less of an effect in situations with large outbreaks. In this study area, applying treatments in active spots and including small-scale blocks and single-tree treatments are important. This can be achieved either by strong beetle surveying/probing to map infestation locations accurately, and strong fell and burn programs, as managers in the area are currently undertaking. To maintain the outbreak at a low level and to minimize eastward spread will require vigilance, especially while the pandemic to the west continues. It will also require management commitment to ensure that survey and fell and burn treatment budgets are available to match changes in the outbreak level over time. Spatially, the outbreak seems most likely to spread through the lower elevation passes into pine stands in the northwest and central portion of the study area (Figure 4). See Fall et al. (2006b) for more details.

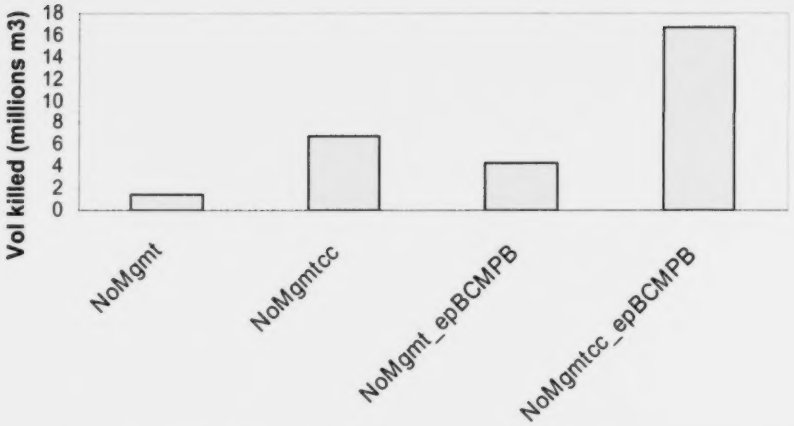

Figure 2. Cumulative volume killed (average of 10 runs over productive forest) for no management baseline runs in Dawson Creek study area. The "cc" suffix indicates use of future 2001-2030 climatic suitability (without a suffix indicates use of historic climatic suitability). The "epBCMPB" suffix indicates application of external pressure from west of the Rocky Mountains via output from the BCMPB provincial scale projection.

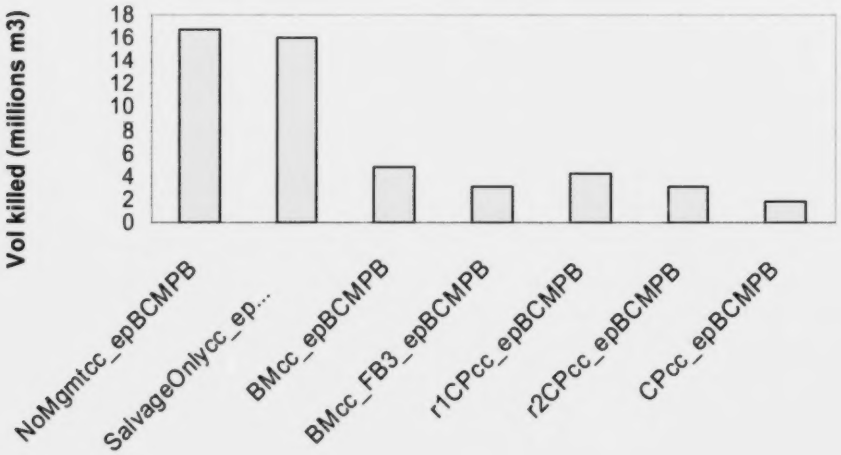

Figure 3. Cumulative volume killed (average of 10 runs over productive forest) in Dawson Creek study area for the base scenarios with climate change ("cc") and external pressure from BCMPB ("epBCMPB"). Scenarios are no harvesting (NoMgmt), salvage focus (SalvageFocus), beetle management focused on population reduction (BM), BM with fell and burn treatment increased three-fold (BMcc_FB3), and current practices focused on reducing population and spread into Alberta (CP, where r1CP and r2CP are intermediate scenarios between CP and BM, see Fall et al. 2006b).

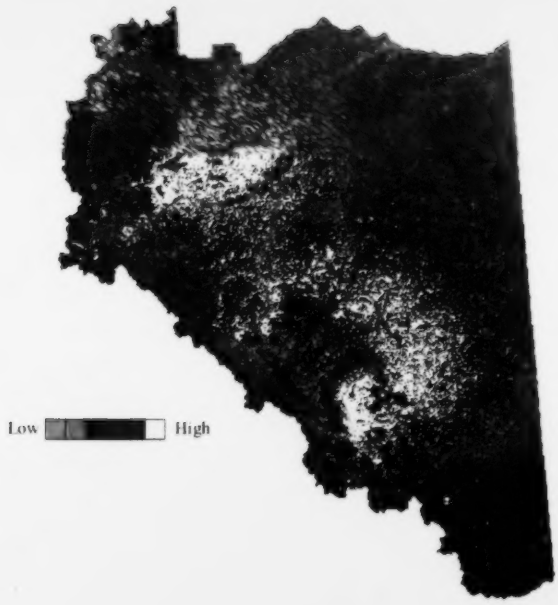

Figure 4. Spatial output showing likelihood of attack defined as the percentage of runs in which each cell is attacked by MPB (regardless of severity), for the NoMgmtcc_epBCMPB scenario: no harvesting, climate change and dynamic MPB pressure from west of the Rocky Mountains.

2.4 Connectivity methods to explore broad-scale risk of mountain pine beetle attack

We adapted connectivity methods using spatial graphs that were developed for assessing woodland caribou habitat in boreal forests (Fall et al. 2007, O'Brien et al. 2006) for examining patterns of MPB hosts. Connectivity is defined as the degree to which pattern impedes or facilitates movement (Taylor et al. 1993). Assessing connectivity of habitat for species of concern at the landscape scale is becoming a key tool for land-use planning and land management (Manseau et al. 2002). In the case of forest pests, the goal is to reduce connectivity, and hence landscape-scale susceptibility, with the aim of slowing rate of spread across a landscape. To do this requires methods to identify areas of high susceptibility that also have high connectivity with other susceptible patches, in particular patches with current MPB attack.

We defined "high susceptibility patches" using an estimate of MPB susceptibility for the study landscape and select areas with susceptibility greater than a certain threshold (e.g., 65%) and larger than a minimum size (e.g., 10 ha). The size threshold should reflect the ecological behaviour of MPB and scale of management. To include a simple measure of cost to contrast with straight-line distance and to capture barriers and conduits to spread, we defined cost units as the relative likelihood and rate of spread compared to high susceptibility patches. For a base cost surface, we defined cost to be 1 for high susceptibility sites, and linearly increasing to a maximum cost (e.g., 10) elsewhere. This assumes that lower susceptibility sites will contribute less to the growth (both amount and conductance) of an outbreak proportional to the susceptibility index level. For example, the cost surface applied assumes that MPB will spread twice as

effectively (either twice as fast or twice as many offspring) through 70% susceptible habitat than in 35% susceptible habitat.

The next step in the process is to identify the patches and extract a spatial graph. As in Keitt et al. (1997), we represent the configuration of susceptible habitat as a mathematical graph. Nodes in a graph consist of habitat patches, while links represent connections between patches. Links track the Euclidean distance or cumulative cost between the two incident nodes, the starting and ending raster position of this vector, and the type of link (see below). A *planar* graph is a graph in which, when drawn on a piece of paper, no two links cross. We define the *minimum planar graph* (MPG) for a patch map as the graph consisting of all links e between nodes n_i and n_j with distance or cost d that satisfy the following:

(i) There is at most one link between each pair of nodes.

(ii) A link cannot cross any other intermediate patches.

(iii) There is no other pair of nodes n_k and n_l that are closer than d to each other with a link that crosses e.

(iv) There is no node n_k that is closer to the landscape boundary than d with a link that crosses e.

The MPG produces a triangulation of the patches with the exception of some patches near the landscape boundary. This triangulation is a generalization of the Delaunay triangulation (Okabe et al. 2000), but has some unique characteristics. Rather than treating patch nodes as points in Euclidean space, the derivation of the MPG explicitly accounts for patch shape. As a result, the links are not necessarily the shortest Euclidean distance links between nodes, as illustrated in Figure 5 below. The graph on the left-hand side shows a patch configuration. Nodes 3 and 4 are closer than 1 and 2, precluding the link connecting nodes 1 and 2 between points c and d. However, nodes 1 and 2 can have a link between points a and b. The graph on the right-hand shows the corresponding mathematical graph with nodes as points, which clearly illustrates the triangulation.

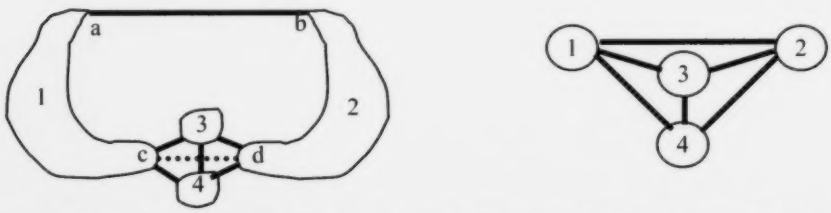

Figure 5. Example minimum planar graph and the underlying Delaunay triangulation.

The same effect is more likely when applying a cost surface, as illustrated in Figure 6, which shows how the shortest link in Euclidean space may not be the least-cost link.

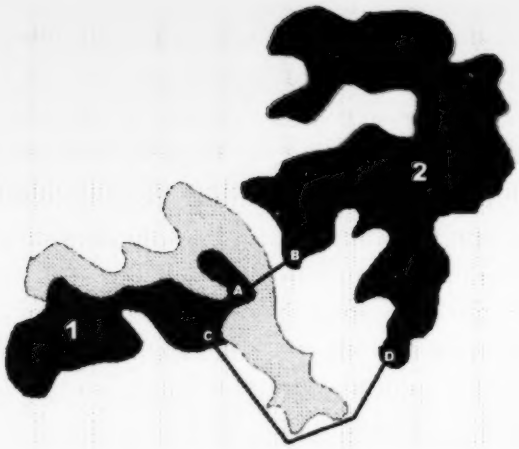

Figure 6. Illustration of the difference between straight-line and least-cost paths linking habitat patches. High quality habitat patches 1 and 2 (black) are connected by a straight-line path (AB) and a least-cost path (CD). The gray area represents relatively high cost.

The minimum planar graph has some useful properties. Both the *nearest neighbour* and *minimum spanning tree* graphs are sub-graphs of the MPG. A nearest neighbour for a node n_i is simply the closest node n_j. The nearest neighbour graph (NNG) contains the set of links between two nodes n_i and n_j, such that n_i is the nearest neighbour of n_j and/or vice versa. The nearest neighbour sub-graph may consist of more than one connected component, but each node has at least one link.

A mathematical *tree* is a graph in which all nodes are connected in a single component and there are no loops. The minimum spanning tree (MST) is the tree for which the sum of all link distances is minimum. The MST consists of all nearest neighbour links plus some other links to create a single connected component. A link between nodes n_i and n_j with distance d is in the MST if there is no path (sequence of links) from n_i to n_j for which all links have distances less than d. The MPG adds further links to the MST to link all nodes that are closest without violating planarity of the graph.

The next step is to analyze the minimum planar graph using the methods of Keitt et al. (1997). We performed a multi-scale analysis over a range of distance thresholds (e.g., from 0 km to 14 km in 100 m increments). At each threshold k we remove all links from MPG that have distances greater than k. We determine the connected components in the resulting graph G' and compute some component level and graph level metrics. At the component level, we determine the number of patches, and the cluster size. At the graph level, we determine the number of clusters and the *expected cluster size* (ECS), which is defined as the sum of the square of cluster size divided by the total amount of habitat (i.e., the area-weighted mean patch size, or expected size of cluster containing a randomly selected hectare of habitat). Expected cluster size is a more appropriate metric for connectivity analysis than mean cluster size, since it focuses on hectares of habitat as the unit rather than patches (e.g., a small cluster should not have the same contribution to the resulting metric as a large cluster). See Fall et al. (2007) for more details.

To account for connectivity with existing attack, we developed methods for "re-orienting" a spatial graph from the perspective of existing attack. After extracting the MPG from the high susceptibility host patches, we *inoculate* patches that contain existing attack by starting in such

patches and then spread outward to other patches to identify the shortest distance or cost through the graph to each node and link. This re-oriented graph can be used for further analysis, such as to identify distance/cost intervals over which connectivity to existing attack is increasing faster or slower.

2.4.1 Tool Application: Mountain Pine Beetle Host Connectivity Analysis in Nadina Forest District

We used Nadina Forest District (previously, Lakes and Morice Forest Districts) as a test-bed for developing the connectivity methods to examine host patterns (Fall and O'Brien 2004). We chose this area because it had a wide range of host conditions, from large areas of high-susceptibility to more fragmented smaller patches of hosts. Given the level of attack currently experienced in this area, we didn't anticipate that the results would be of high interest to local managers, who are more focused on salvage efforts at this point.

We applied and refined the graph-based connectivity methods described previously for examining patterns of high susceptibility patches. This analysis helps to identify the scales at which habitat patches become connected, important links/corridors, as well as the relative importance of individual patches at various scales. The methods we applied consider distance as measured in Euclidean (straight-line) space or in "movement cost" (least-cost) space where a unit of movement may be higher/lower cost depending on the presence of barriers (Bunn et al. 2000). For example, relative to late-seral pine forest, lakes and unsuitable hosts may have high dispersal impedance for MPB, while mid-seral pine stands and mixed species stands may present less of a barrier. In this analysis we differentiate cost based on susceptibility, although directional costs such as prevailing wind could be incorporated in future analysis.

Cross-scale analyses are important to assess the distance thresholds at which a landscape becomes fragmented and to identify habitat patches of particular importance at a given scale. The straight-line analysis identified three main critical scales at which connectivity changes (3 km, 5 km, and 6.5 km). The least-cost path analysis identified four main critical scales (17 km, 27 km, 32 km and 42 km, in units of "effective distance"). We found that high susceptibility patches are quite well connected at low distance thresholds in the southern part of the study area, at moderate distances in the south-central portion of the district and at longer distances in the central and northern areas. We also identified patches that were particularly important to maintain patch connectivity at various scales. Large patches in the south and centre of the landscape are critical at small distances, while stepping-stone patches that provide linkages among more scattered patches are critical at larger distances. Incorporating movement cost information into the analysis allowed inclusion of spatial variability in dispersal barriers and conduits. We found that this changed the critical scales and the key patches that have a higher than expected contribution to connectivity. The least-cost path analysis also helps to identify movement corridors since paths are aligned through less costly regions of the landscape.

2.4.2 Tool Application: Mountain Pine Beetle Host Connectivity Analysis in Dawson Creek and West-Central Alberta

The connectivity approach applied in Nadina Forest District helped identify aspects of spatial graph analysis that were useful for MPB risk assessment and elements that required further research. In particular, we learned that these methods are more appropriate in areas with newly emerging attack, such as in Dawson Creek and western Alberta, or with risk of future attack.

Areas with existing attack are best assessed with more dynamic methods, such as the SELES-MPB landscape-scale population model. We also learned that the base methods for examining overall connectivity of hosts were unable to fully capture risk of spread. To address this deficiency, we developed methods to integrate a spatial graph of MPB host patterns with spatial information on existing attack. This allowed us to "reorient" a spatial graph so that the degree of connection of high-susceptibility host patches to existing attack could be quantified, which can be interpreted as a ranking on likelihood of attack.

We applied this approach to a large study area that included the Dawson Creek area in BC, and Jasper National Park, Wilmore Wilderness Area and a number of forest management units from the BC border to Slave Lake north of Edmonton in Alberta (Figure 7). We found that, using the default parameters, connectivity of susceptible host stands (stands with susceptibility ≥ 65) to current attack increased rapidly up to 65 km effective distance, between about 150 to 250 km effective distance, and between about 350 to 440 km effective distance (Figure 8). Between these ranges, connective increased relatively slowly. The plot in Figure 8 helps to identify these threshold ranges, but a key strength of this approach is the ability to map these thresholds spatially to show areas of higher and lower connectivity (Figure 7). Areas with relatively low connectivity represent areas in which MPB may spread more slowly, and focus may be warranted to treat stands to reduce connectivity further. Areas with relatively high connectivity represent higher risk, and likely lower management potential if MPB become established.

Several presentations have been made on the methods and results of this analysis, with feedback helping to refine the approach and improve utility of results. Discussions with forest managers indicated that this information was useful to help prioritize areas for treatment. For example, a stand with moderate susceptibility, but in a well-connected location, may be more important to treat than a stand with high susceptibility, but poorly connected to other host stands. A publication on these methods is underway that uses MPB survey information from 2006 for model verification.

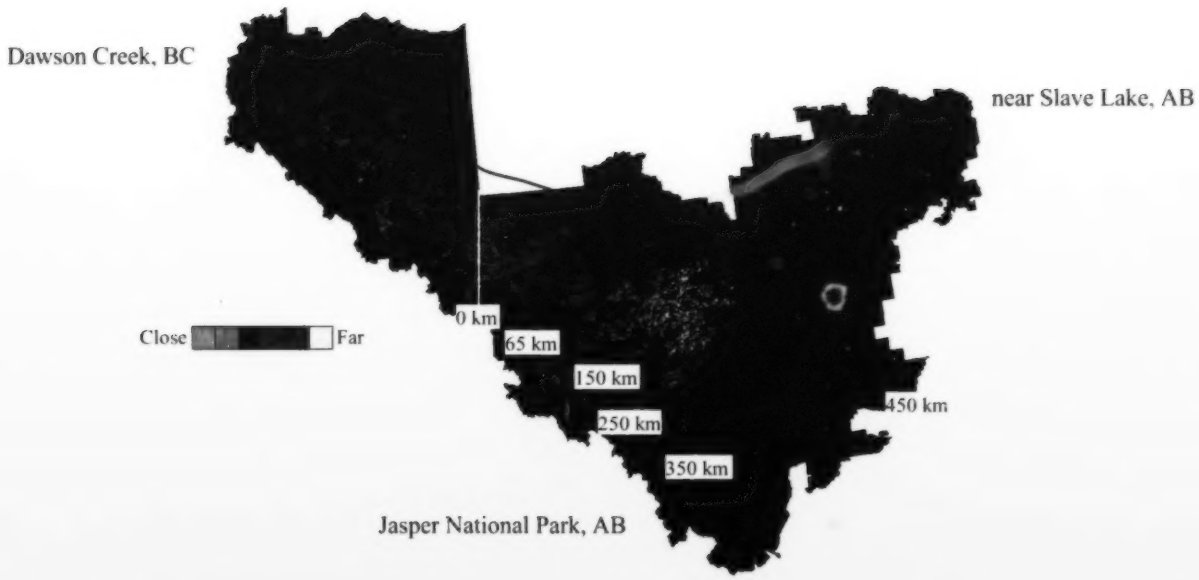

Figure 7. Host connectivity to existing attack in Dawson Creek/west-central Alberta study area. The colours on host stands represent degree of connectivity. The isolines partition these based on the thresholding analysis that was used to identify threshold distances with relatively high or low increase in connectivity to existing attack (Figure 8).

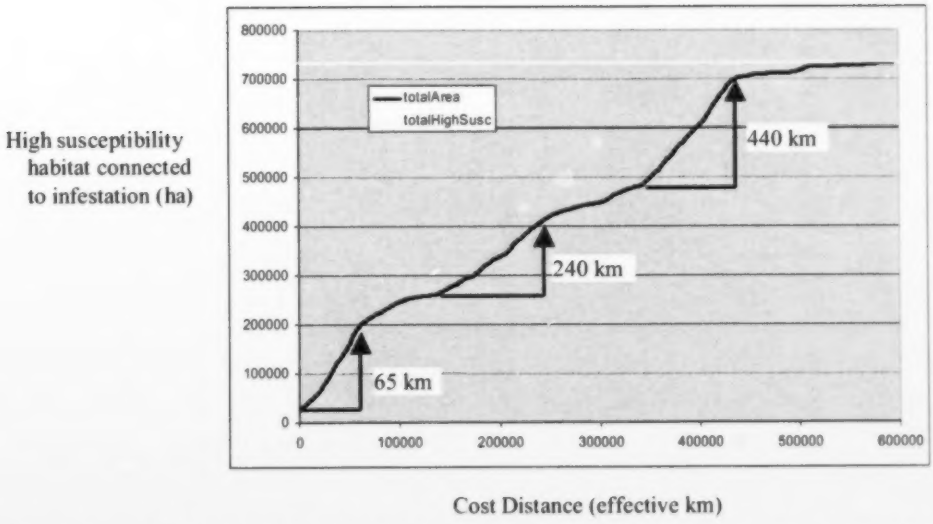

Figure 8. Results of the spatial graph thresholding analysis in the Dawson Creek/west-central Alberta study area. The x-axis is the distance (in cost units, or effective distance in km) to existing attack above which stands are assumed to be disconnected. The y-axis is the area of high susceptible stands connected to existing attack at a given cost threshold. Arrows indicate scales over which there are rapid increases in connectivity to existing attack.

3 Documents, Presentations and Posters

A complete list of deliverables related to this project can be found in the Appendix.

4 Extension and Further Linkages

The tools and results of our project have been transferred to collaborating organizations. We successfully transferred the updated susceptibility rating system to Alberta Sustainable Resource Development (ASRD), who used it for all pine stands in Alberta.

There have been a number of new projects initiated by recipients of information from this Mountain Pine Beetle Initiative (MPBI) project and a related previous MPBI project headed by M. Eng (Eng et al. 2005). In conjunction with the Bulkley Valley Institute and Research Branch of the BC Ministry of Forests and Range, A. Fall helped explore impacts on timber supply in Morice timber supply area and Vanderhoof Forest District (Fall et al. 2006a), with a focus on mid-term harvest potential and the role of residual stand structure.

The BC Forest Service is using results of our MPB projections to assess timber supply in MPB-affected management units. A. Fall has been working with Forest Analysis and Inventory Branch to train usage of models developed in part by the MPBI projects to perform timber supply analysis to support the chief forester in determining annual allowable harvest levels.

In western Alberta, there is a high correlation between susceptible hosts for MPB and suitable habitat for woodland caribou (*Rangifer tarandus*), a threatened species in Canada. Alberta Sustainable Resource Development has initiated a project in conjunction with the Canadian Forest Service (T. Shore, B. Riel) and Gowlland Technologies Ltd. (A. Fall) to use the landscape scale MPB population model, SELES-MPB to explore interactions between management strategies, MPB and caribou habitat.

At a request from Forest Management Branch, Department of Energy, Mines and Resources, Yukon Territorial Government, we embarked on a project to adapt our methods for landscape scale risk of MPB attack to an ongoing spruce bark beetle (*Dendroctonus rufipennis)* infestation in southwestern Yukon. We have held two workshops and collaboratively chose to adapt the connectivity methods developed in part under this project to examine potential spread of the spruce beetle.

Based on interest in expanding our study area, T. Shore initiated a project to examine connectivity of jack pine and lodgepole pine over the entire provinces of Alberta and Saskatchewan. Data requirements are significant, and the first year was primarily devoted to assembling data and performing preliminary runs. Additional challenges posed by this project are the scale of the study area. To handle such a large area with relatively fine resolution assessment (1 ha grid cells), we are developing methods of decomposing a study area for extracting spatial graphs, and recomposing graphs, enabled by ensuring adequate overlap between sub-areas.

5 Conclusion

This project made significant advances in the development of Decision Support tools for management of the mountain pine beetle. Through the incorporation of climatic suitability surfaces into the susceptibility and risk rating systems, population dynamics and impact model (MPBSim), spatial dispersal and management models in SELES-MPB, and spatial graph

connectivity analysis, these tools become more sensitive and accurate. These improvements have had the impact of putting better information into managers' hands for decision-making and for examining potential effects of estimated future climate.

In addition, this project addressed the need for information on the potential for geographic spread of this insect under climate change scenarios in Dawson Creek and west-central Alberta. A major concern for Canada is that the devastating losses to the pine forests of British Columbia could extend to Alberta and beyond. We started to address this concern through modelling beetle dispersal and impact under current and future climate scenarios and through the connectivity assessments. This will help to provide an "early warning" system that is required for pro-active management.

Interest and utility of the tools and results is demonstrated by the applications done as part of this project, and the ongoing collaborations stemming from the tools enhanced via this project.

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